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I. BACKGROUND

In 1990 NASA initiated its Generic Hypersonics Research Program (GHP). The general objectives of this research program are to develop a technology background required for aeronautical research in the hypersonic Mach number flow range. These research efforts are to complement the National Aerospace Plane (NASP) program and are geared to the development of experimental and computational fluid dynamics (CFD) techniques. Previous experience under the current research effort using a two-dimensional full Navier-Stokes code (SCRAM2D) has indicated the desirability of producing highly contoured internal portions of a hypothetical Mach 10 inlet. These results were presented in the previous two progress reports. Both the two-dimensional and three-dimensional codes were used. The two-dimensional code was used in a parametric investigation to design the contours for a hypothetical Mach 10 inlet. The flow conditions hypothesized to enter the inlet were taken from the experimental conditions available in the NASA-Ames 3.5 foot hypersonic wind tunnel. The 2D code was used parametrically as a design tool because of its reasonable results, ease of use and relatively short computer turnaround time.

In the previous progress report, for 1 January through 30 June 1991, the 2D compression contours (ramp and cowl) generated with the 2D code were assumed to be those for a three-dimensional inlet, and the three-dimensional Navier-Stokes code (SCRAM3D) was used to investigate the resulting three-dimensional flow fields that occurred when swept sidewalls were added to the 2D compression contours. Significant results of the previous investigating period indicated that the flow obtained within the three-dimensional solution did not deviate markedly from that obtained with the 2D code. This

result gives credence to the continued use of the 2D code for parametric design studies aimed at optimizing inlet flow field behavior.

One of the prominent goals of inlet design for high speed applications is to produce an inlet that delivers uniform flow at its exit in the shortest possible distance. In previous studies, the technologies for determining contours for both the ramp and cowl were demonstrated that allowed a nearly shock free exiting flow field to be obtained. This technology was developed further in the present reporting period and applied to a preliminary design investigation of a biconic hypersonic research vehicle with a nearly two-dimensional inlet attached near the aft end of the vehicle. This report describes the results of a parametric investigation of this proposed inlet for freestream Mach numbers between 10 and 15.

II. INTRODUCTION

NASA is currently contemplating an augmentation to the Generic Hypersonics Research Program that would embody a flight test vehicle launched as a portion of the Pegasus rocket system. Preliminary investigations have centered around a geometry that is a biconic vehicle approximately 20 feet long. The initial cone is assumed to be sharp and have an angle of 5 degrees. The second cone of the biconic is a 4-degree, half-angle deflection, for a total half angle second portion of the biconic of 9 degrees. For purposes of design, it was assumed that the biconic vehicle could operate at an altitude of 85,000 feet between Mach numbers of 10 and 15. These conditions produce a very high dynamic pressure of nearly 7000 psf. The code used here is the SCRAM2D code with the variable gamma, perfect gas option. In this option, gamma is assumed to be a known, temperature-dependent function, and no air- or reacting-gas chemistry is included. The axially symmetric version of the code was used to describe the conical flow fields. The proposed cowls discussed here are also assumed to be axially symmetric. It should be noted, however, that by the time the inlet cowl lip is encountered the body has a sufficiently large radius to consider the flow nearly planer two-dimensional at that point. However, for consistency, the axially symmetric code was used throughout the study. The objective was to obtain a combuster pressure, that is an inlet exit pressure, of between a half and one atmosphere. The previously developed technology was assumed to be applicable in determining contoured ramp and cowl lines for the inlet.

III. RESULTS AND DISCUSSION

The biconic vehicle body and resulting flow field solution for the Mach 15 design operating at Mach 15 is shown in Figure 1. Figure 1a shows the geometry and Mach contours to actual scale while Figure 1b shows these contours with an expanded vertical scale. Figure 1c shows the internal flow detail, showing several important features of the assumed arrangement of the geometry and the flow field. In Figure 1b, the initial conical shock intersects with the second conical wave ahead of the assumed location of the cowl lip station. A slip line divides the upper and lower portions of the flow field, as seen clearly in Figure 1c. In this study the slip line is ingested into the inlet for the currently assumed cowl position. The boundary layer on the biconic is assumed to undergo transition at the beginning of the 9 degree section of the body. Upstream of that, the boundary layer is assumed to be laminar, and downstream assumed to be instantaneously turbulent and described by the mixing length turbulence model used extensively throughout this study. The effect of ingesting the slip line in the actual flight experiment is not fully understood at the present, however, since variations in the Mach number that exist across the slip line are relatively small, it is ignored here. Figure 1c indicates the location of the cowl that is assumed to have a sharp lip and to have an initial segment that is aligned with the flight direction. This produces a cowl shock wave that interacts with the ramp boundary layer, producing a pressure field as shown in Figure 1d. A typical characteristic of hypersonic cowl shock wave/thick boundary layer interactions is the expansion seen in Figure 10 from the back side of the first ramp boundary layer-cowl shock wave interaction. In the present design, this expansion is canceled by turning the cowl downward at the appropriate streamwise location. The cowl shock reflects from the ramp boundary layer and crosses the

inlet flow field, interacting with the cowl boundary layer, which is assumed to be laminar throughout the inlet. The reflected cowl shock wave is canceled on the cowl by turning the surface away from the ramp. As seen in Figure 1d, the cancellation is quite effective. Further details of this particular design are discussed in comparison with a reference case using a straight cowl later in this report.

The off-design performance of the highly contoured cowl is of interest, since, to be practically useful, the fixed contour would have to work over a wide range of flight conditions. One off-design case was investigated here to determine the effectiveness at a lower Mach number. Figure 2 shows the application of the 2D code to a case using the Mach 15 design contours for which the freestream Mach number is assumed to be 10. Figure 2a shows the Mach contours for the actual vertical scale while Figure 2b shows an expanded vertical scale. For this case, the initial cone shock wave and the second cone intersect at a radius nearly equal to that of the cowl lip. This provides a uniform conical flow field entering the inlet. Again, the geometry is the same as that in Figure 1, including the location and magnitude of the cowl contours. Figure 2c shows the detail of the internal flow section, which indicates several important features. First of all, the entering boundary layer, relative to the cowl lip height, is significantly thinner due to the reduced freestream Mach number. Secondly, the placement of the cowl contouring produces a very good outflow uniformity. This is true because the internal shock wave angles are not substantially different between the Mach 15 and Mach 10 cases. Pressure contours shown in Figure 2d confirm that the pressure is also reasonably uniform exiting the inlet and effective shock cancellation due to the contouring exists. The absolute pressure level for the Mach 10

condition is about half of that for the Mach 15 condition (approximately a half of an atmosphere) since the dynamic pressure is about half for the Mach 10 condition.

For purposes of comparison with this last solution, a parametric design was undertaken at the Mach 10 condition in order to produce a set of contours that might be considered optimal for the Mach 10 freestream condition. The results of the Mach 10 design are summarized in Figure 3, which presents similar information to that presented in Figures 1 and 2. No substantial changes in contour were needed in order to optimize the design for Mach 10.

The last two figures demonstrate a range of usable Mach numbers that a hypothetical contoured cowl design can have. The effectiveness at low supersonic Mach numbers has not been investigated. Again, these contours were obtained using the 2D code, although as mentioned previously and demonstrated in the last reporting period status report, few significant effects arise in terms of the overall compression ratio and performance of the inlet due to 3D flow field effects as long as these 3D effects don't lead to an inlet unstart. This is true in spite of the fact that local flow distortion may arise due to the ingestion of sidewall flow.

In order to demonstrate the value of the design technology demonstrated here, a comparison between a straight cowl and the Mach 15 design contour cowl (both configurations operated at a Mach 15 condition) is shown in Figure 4. Here the static pressure ratio contours are shown to a very enlarged scale in the internal flow portion of

the inlets. Figure 4a shows the results of the straight cowl with its characteristic, reflecting oblique shock wave train continuing throughout the length of the inlet. Figure 4b shows the results from the contoured cowl Mach 15 design to the same scale and clearly indicates the nature of the shock cancellation characteristics of this design. The Mach 15 design inlet has a very short ratio of internal flow length to throat height. The behavior of the straight cowl and its attendant oblique shock wave train results in the requirement for longer isolator ducts. With the oblique shock train, each successive shock wave-boundary layer interaction results in additional losses and performance penalties. The boundary layers on the surfaces become weaker the longer the isolator section is, leading to possible upstream propagation of disturbances from the combuster. In contrast, the Mach 15 design produces a very uniform flow in a very short distance, satisfying the design objectives stated in the introduction. The quantitative nature of the comparison is shown in Figures 5 and 6. Figure 5 shows a representative surface pressure distribution from the ramp of the biconic body within the internal flow section for both the straight and contoured cowl geometries. Although variations exist for the contoured cowl case, they are not of the strength and presumed duration of the variations exhibited for the straight cowl configuration. Figure 6 shows a comparison of the static pressure profile at the exit of the inlet for the straight contoured cowl geometries. The straight cowl geometry exhibits a large expansion region and a shock wave in the center of the inlet at the outflow station. The comparable station for the contoured cowl indicates a relatively uniform outflow of pressure, although it is at a higher absolute pressure level due to the additional internal compression for the contoured cowl design.

During the course of the present reporting period, questions arose as to the pressure levels that might be encountered in the Mach 15 design inlet should an unstart occur in flight. A preliminary investigation was carried out to simulate an unstart occurring due to a back pressure near the exit of the inlet. The over-pressuring in this CFD simulation was produced by injecting fluid on both the biconic body and cowl surfaces into the flow stream. The 2D axi-symmetric code was run in a time-accurate mode to ensure resolution of the transient pressures during the inlet unstart. The trace of the simulated surface pressures on the ramp and cowl for this unstart is shown in Figure 7. This figure shows the absolute pressure located near the minimum area of the inlet as a function of time. For short times, both the cowl and ramp pressures are at a level of approximately 2,000 psf and represent the exit conditions for the on-design operating inlet. At zero time on this figure, the injection was turned on. Approximately one-third of a millisecond is required for the effects of the injection to be felt near the minimum area. At this time the pressure begins to rise, until approximately 1.2 milliseconds into the sequence a peak pressure of between 80,000 and 100,000 psf is obtained. This pressure corresponds in magnitude to a value of pressure that would be obtained across a normal shock wave at the minimum area Mach number (about 6 to 6.5) for the pressure in the operating inlet. Later in the time history, the pressure falls to another plateau and remains constant from about 2 milliseconds on. The latter plateau pressure is one corresponding to a total inlet unstart with a series of oblique and normal shock waves occurring ahead of the cowl lip station. This transient produces very large pressures for a short time that will have to be recognized in the design phase in order to maintain the structural integrity of the system. In the event that structural integrity of the inlet cannot be assured, one alternative is to design the cowl structure to separate cleanly from the vehicle.

IV. CONCLUSIONS

The design technology using the full Navier-Stokes 2D code (SCRAM2D) developed previously in the present study has been used to examine the hypothetical flow field expected to occur within an inlet on a biconic body flown between Mach numbers of 10 and 15 at 85,000 feet. A contoured cowl surface and radiused ramp shoulder provide effective shock cancellation producing a high performance inlet with a very short length. An inlet was designed for a freestream Mach number of 15 and was shown to have excellent outflow characteristics. This Mach 15 design was run in the numerical simulations for a freestream Mach number of 10 and shown also to have good flow quality. A set of contours was designed for Mach 10 which resulted in only slight changes away from the Mach 15 design. Comparisons between a traditional straight cowl and the contoured cowl at Mach 15 clearly showed the advantages of using a contoured cowl. Finally, a back pressure unstart was simulated and shown to produce very high pressures (up to 100,000 psf) during the unstart transient.

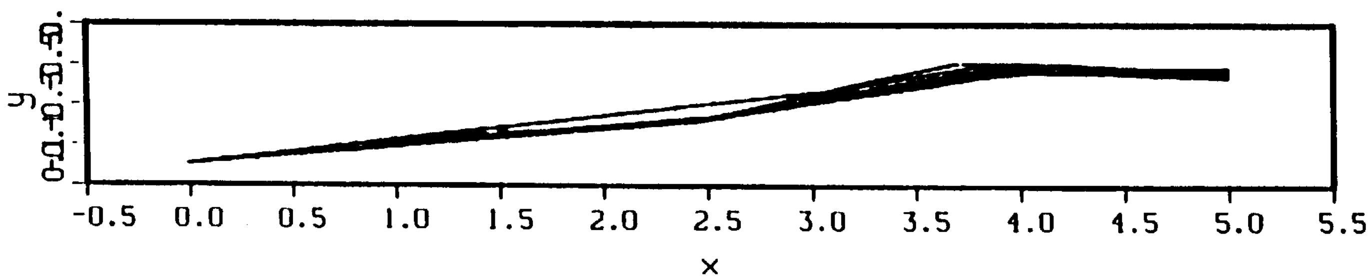

FIGURE 1 **Preliminary Design for Contoured Cowl, M = 15 Design at M = 15**
a) Actual Vertical Scale, Mach number contours

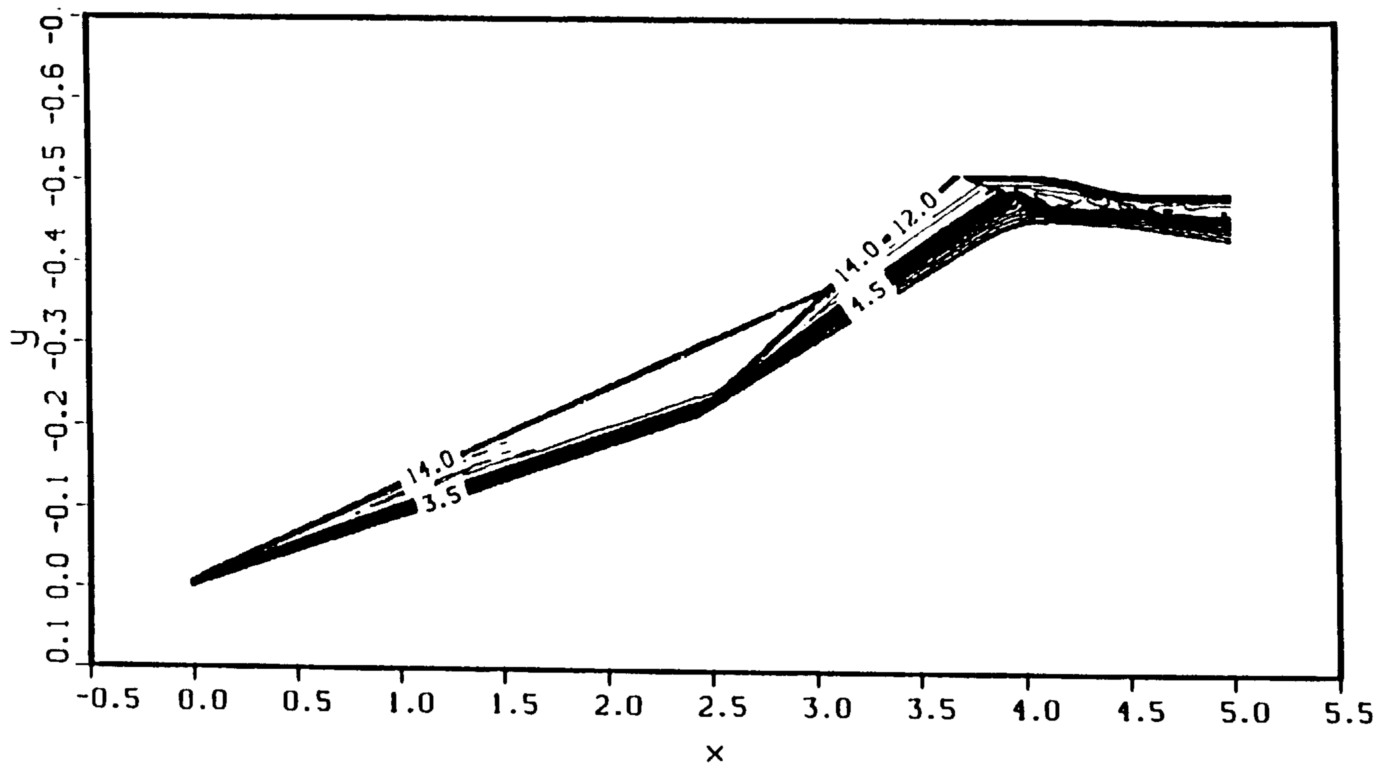

FIGURE 1 Continued.
b) Expanded Vertical Scale, Mach number contours

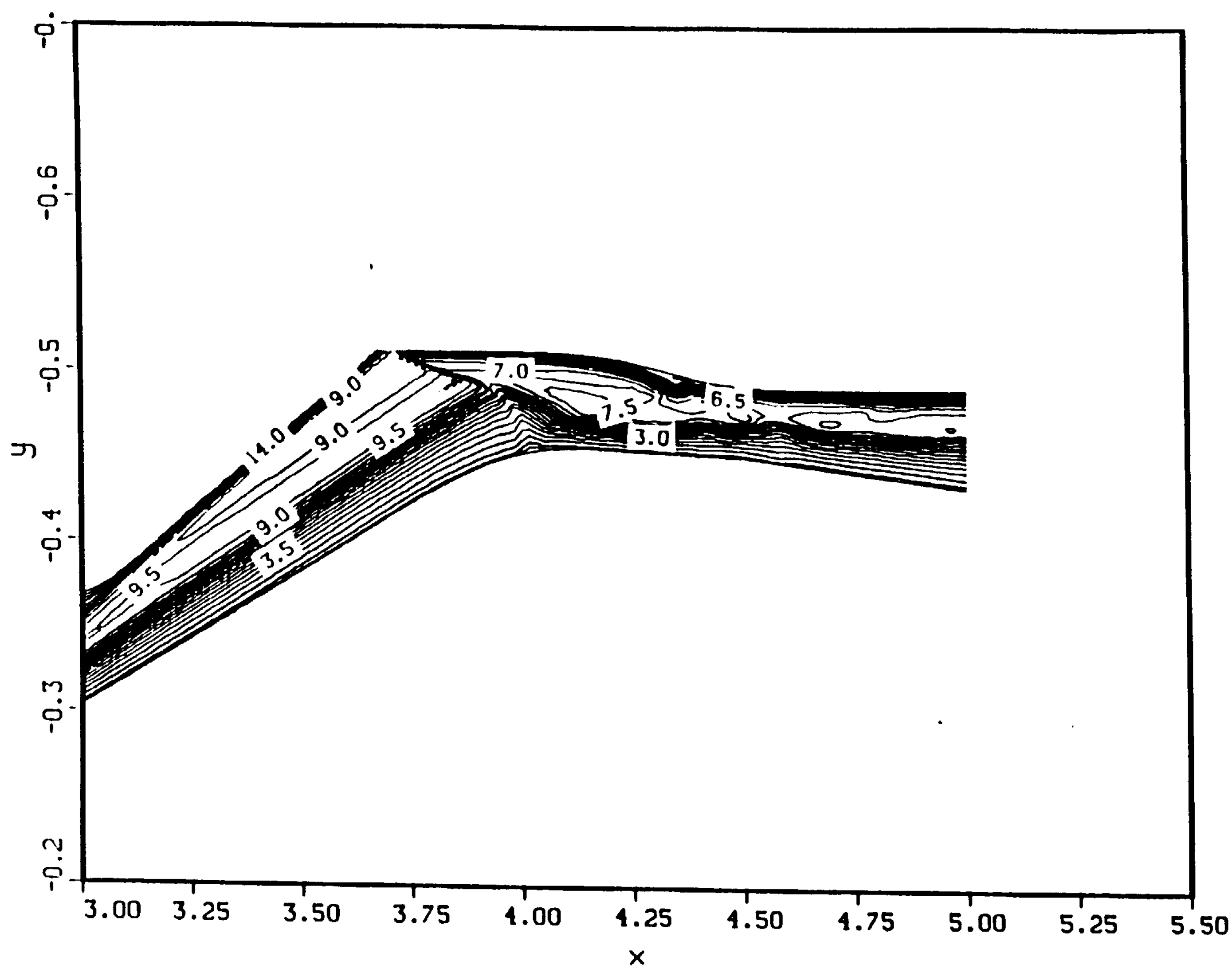

FIGURE 1 Continued.
c) Internal Flow Detail, Mach number contours

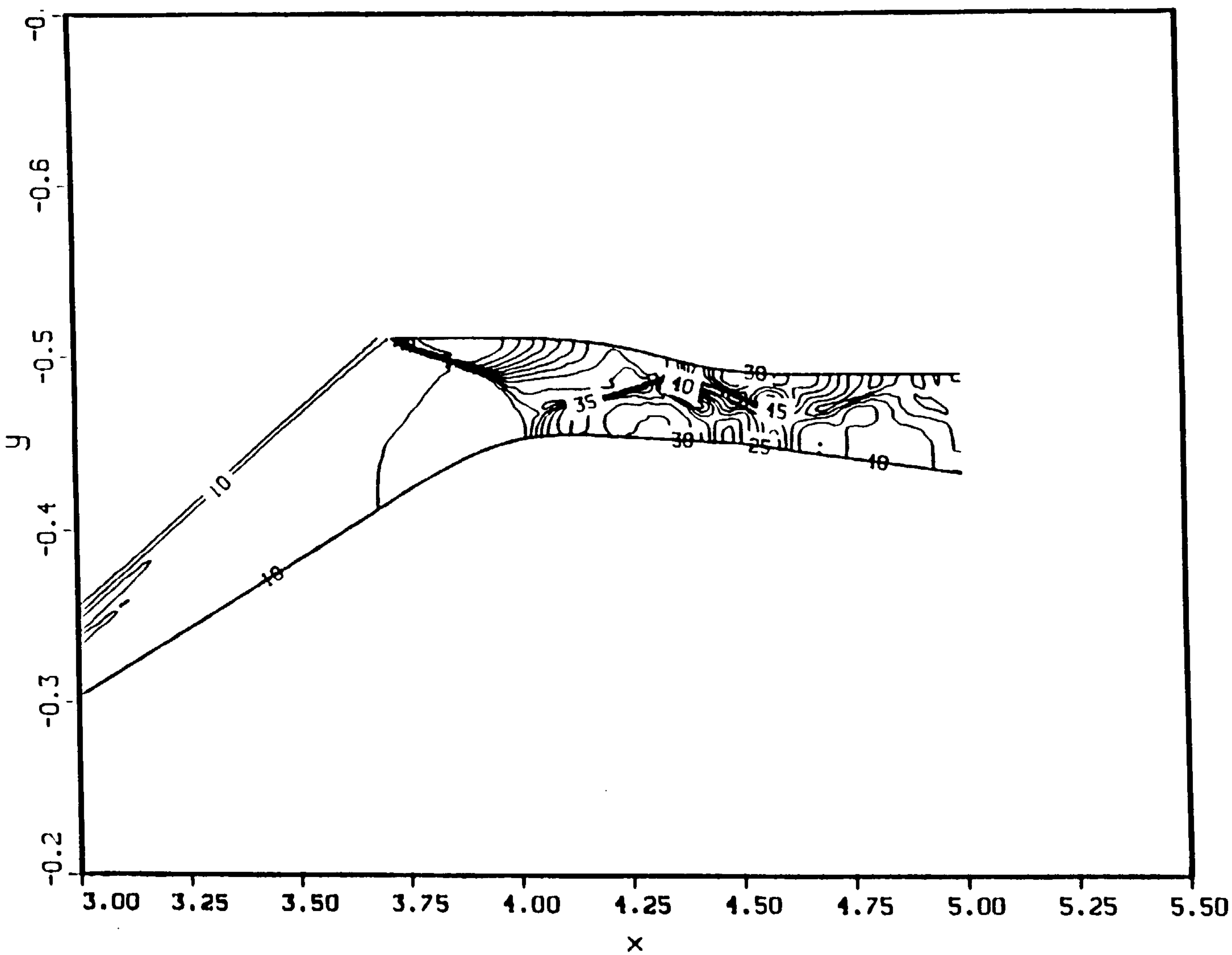

FIGURE 1 Concluded.
d) Internal Flow Detail, Pressure contours

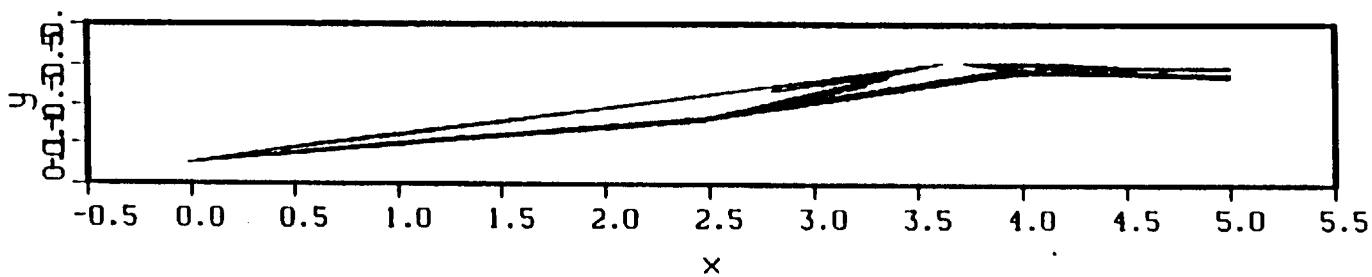

FIGURE 2 **Preliminary Design for Contoured Cowl, $M = 15$ Design at $M = 10$**
a) Actual Vertical Scale, Mach number contours

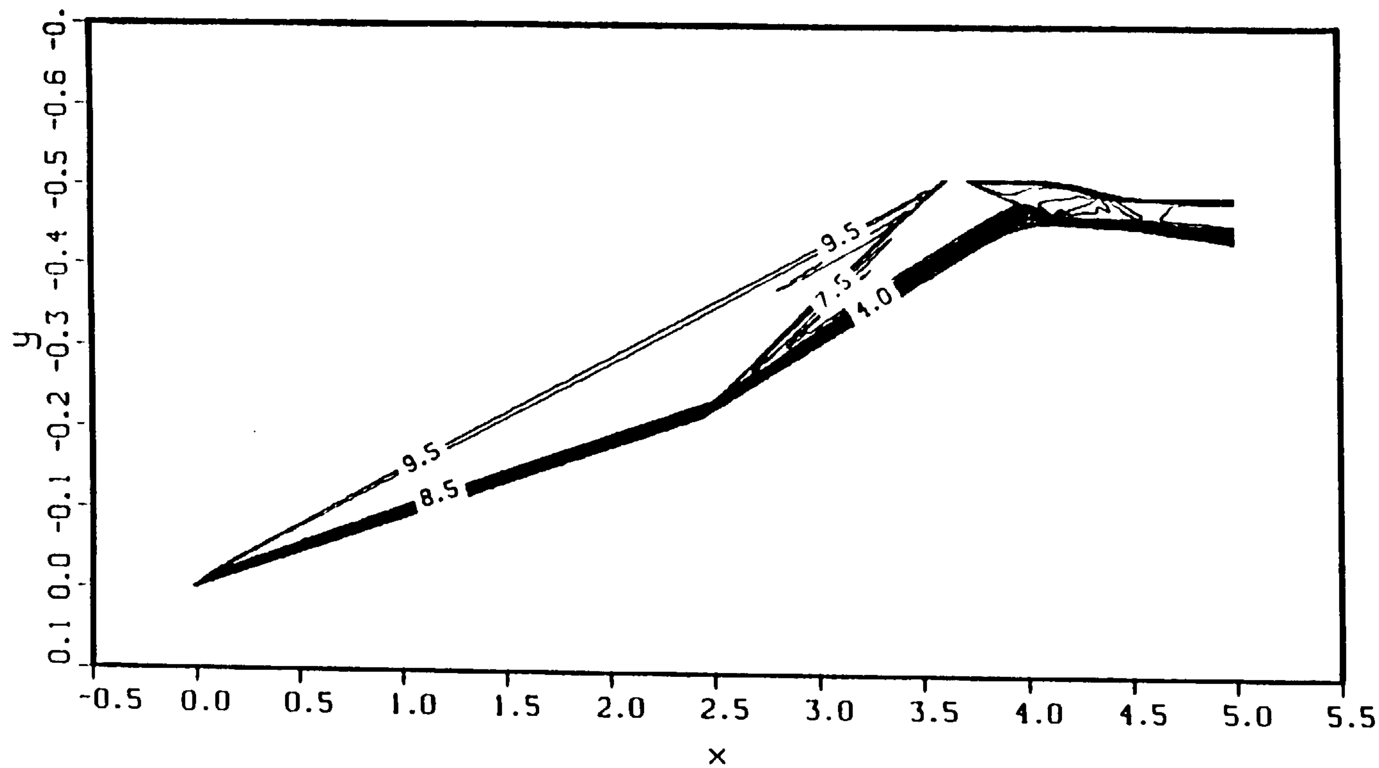

FIGURE 2 Continued.
b) Expanded Vertical Scale, Mach number contours

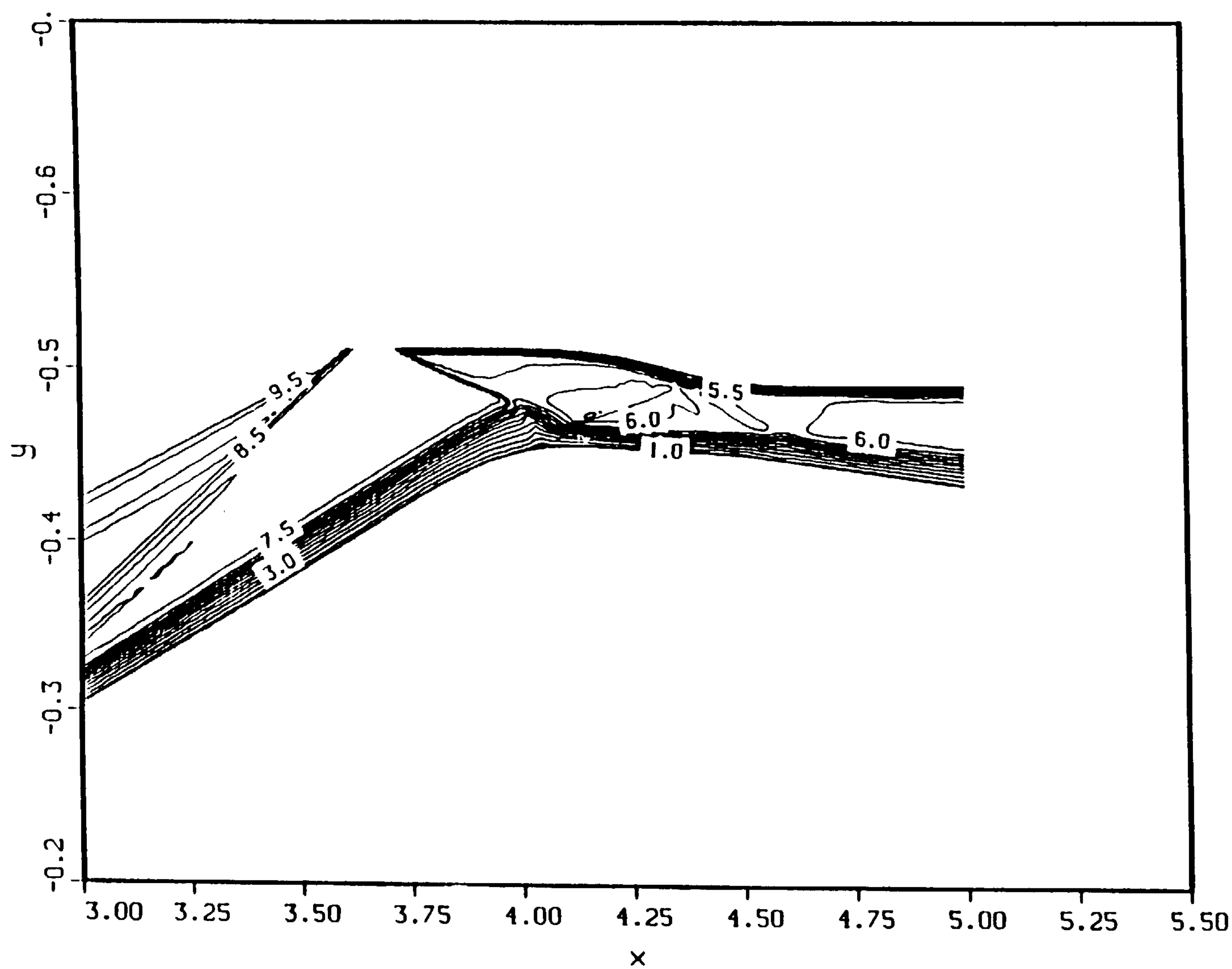

FIGURE 2 **Continued.**
c) Internal Flow Detail, Mach number contours

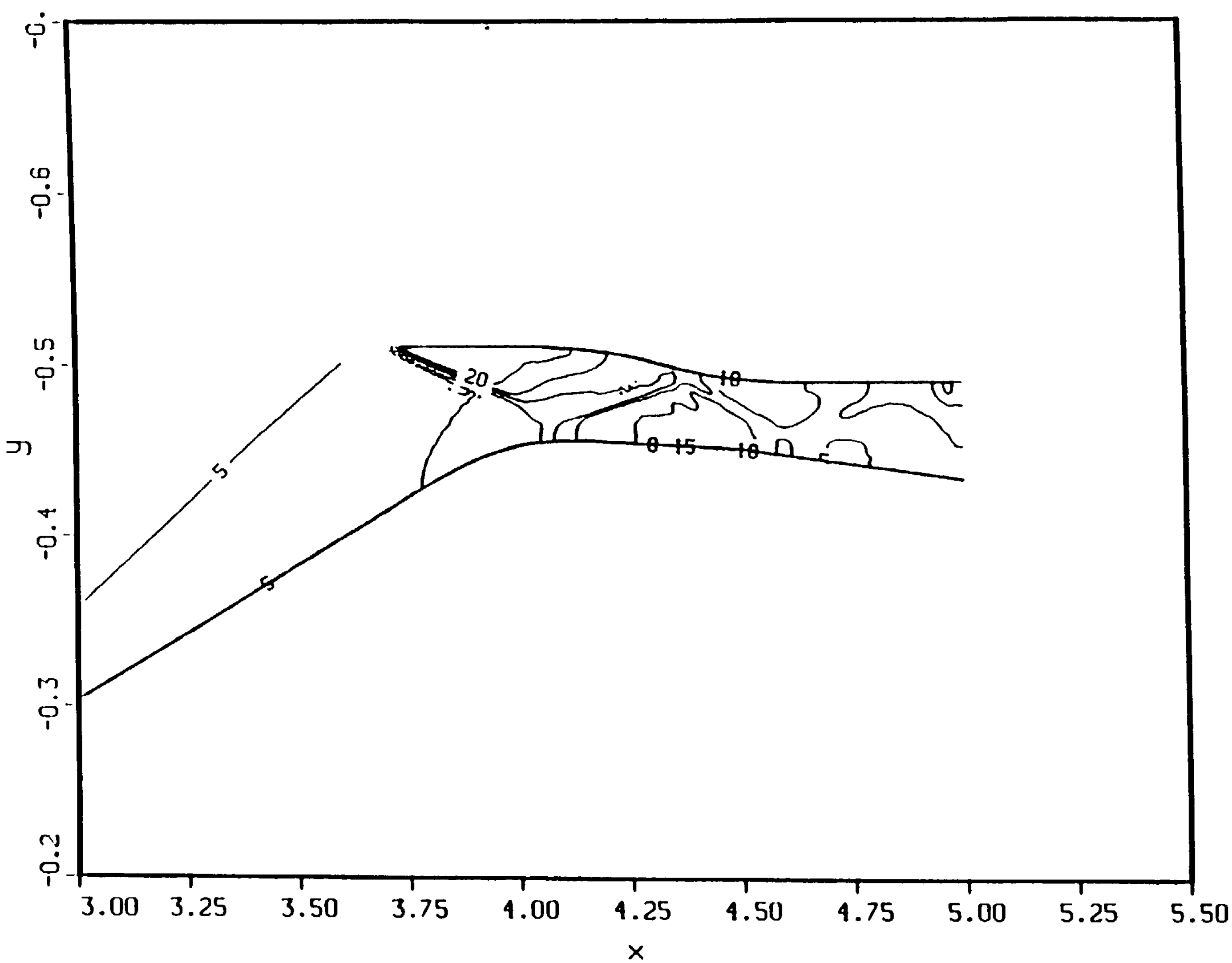

FIGURE 2 **Concluded.**
d) Internal Flow Detail, Pressure contours

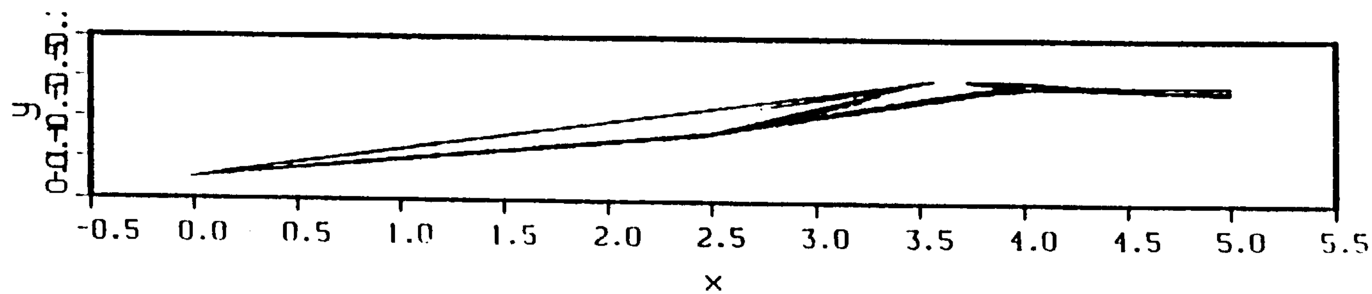

FIGURE 3 Preliminary Design for Contoured Cowl, M = 10 Design at M = 10
a) Actual Vertical Scale, Mach number contours

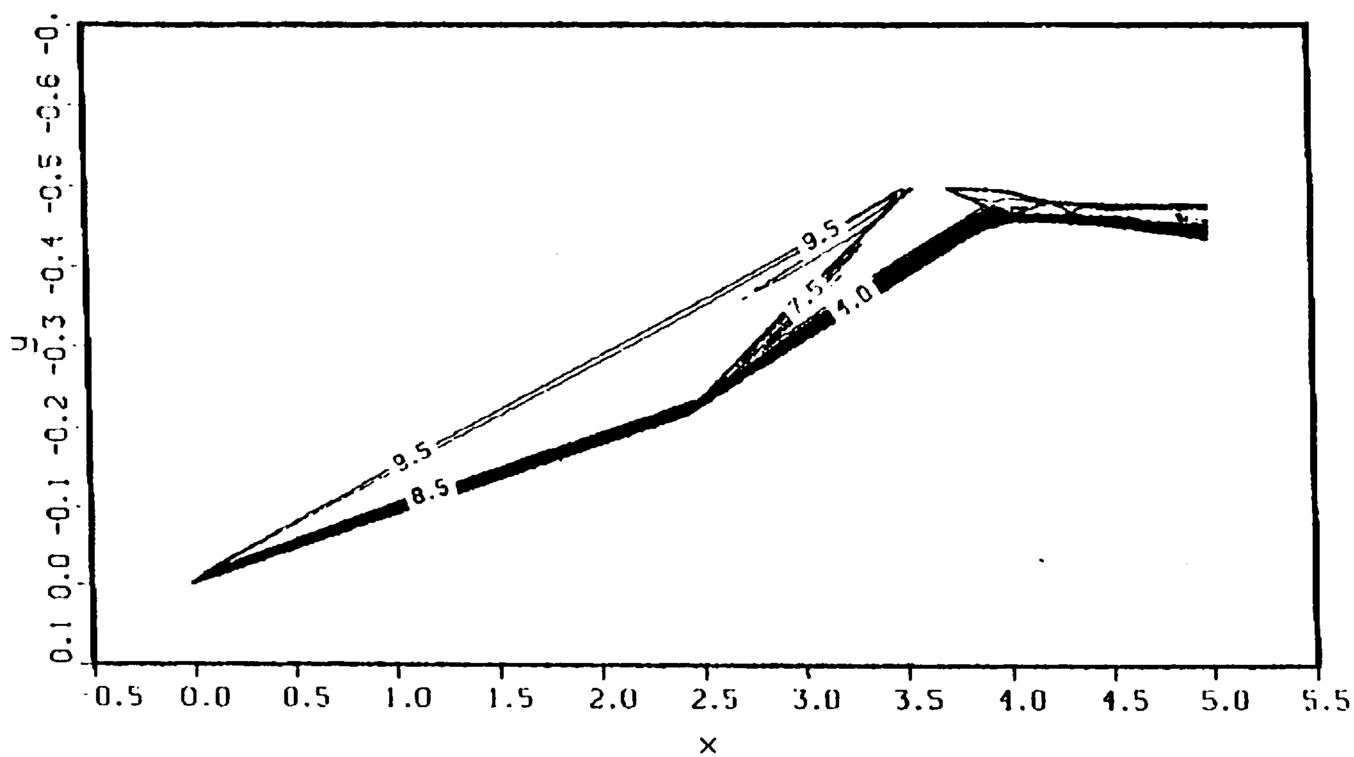

FIGURE 3 **Continued.**
b) Expanded Vertical Scale, Mach number contours

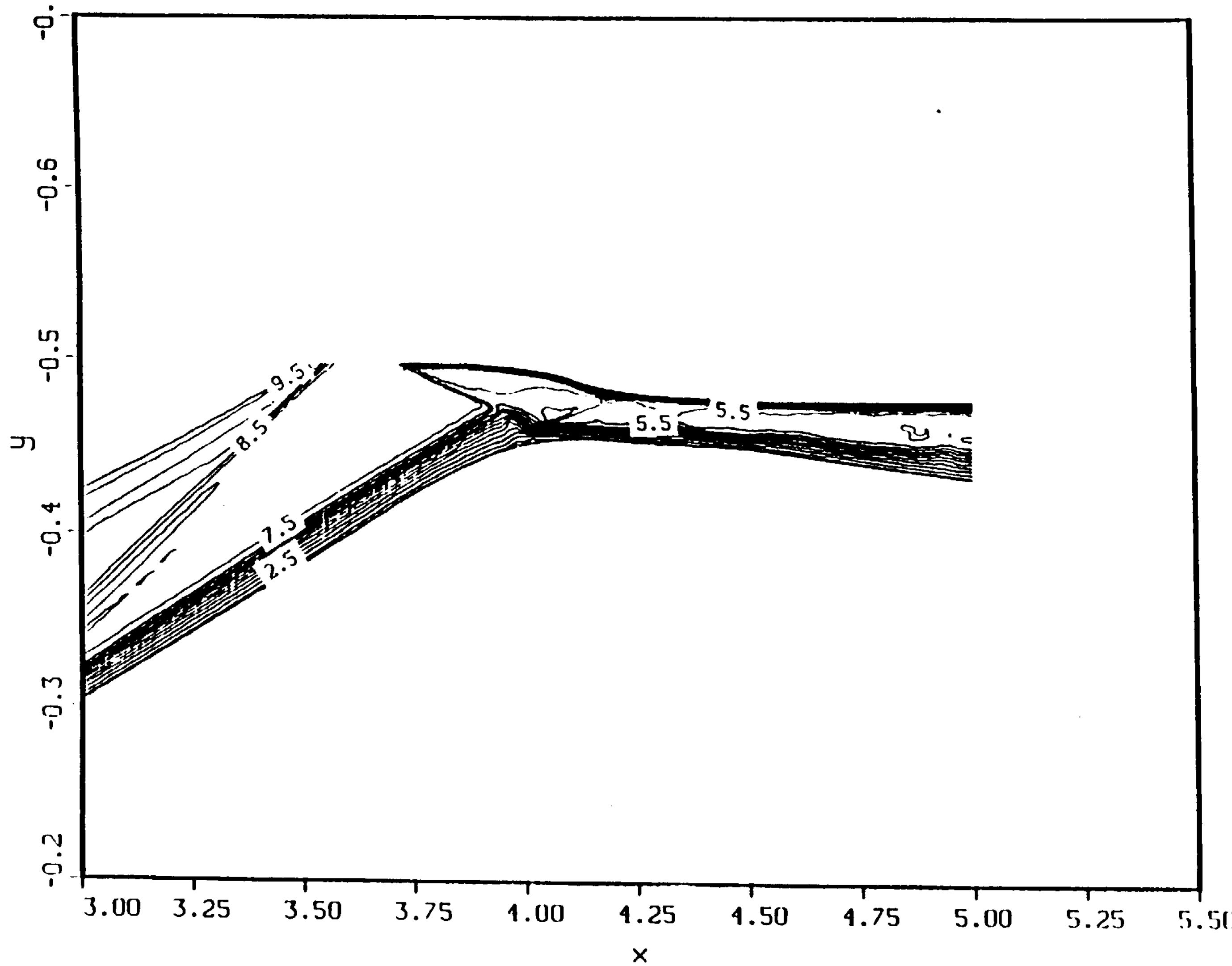

FIGURE 3 **Continued.**
c) Internal Flow Detail, Mach number contours

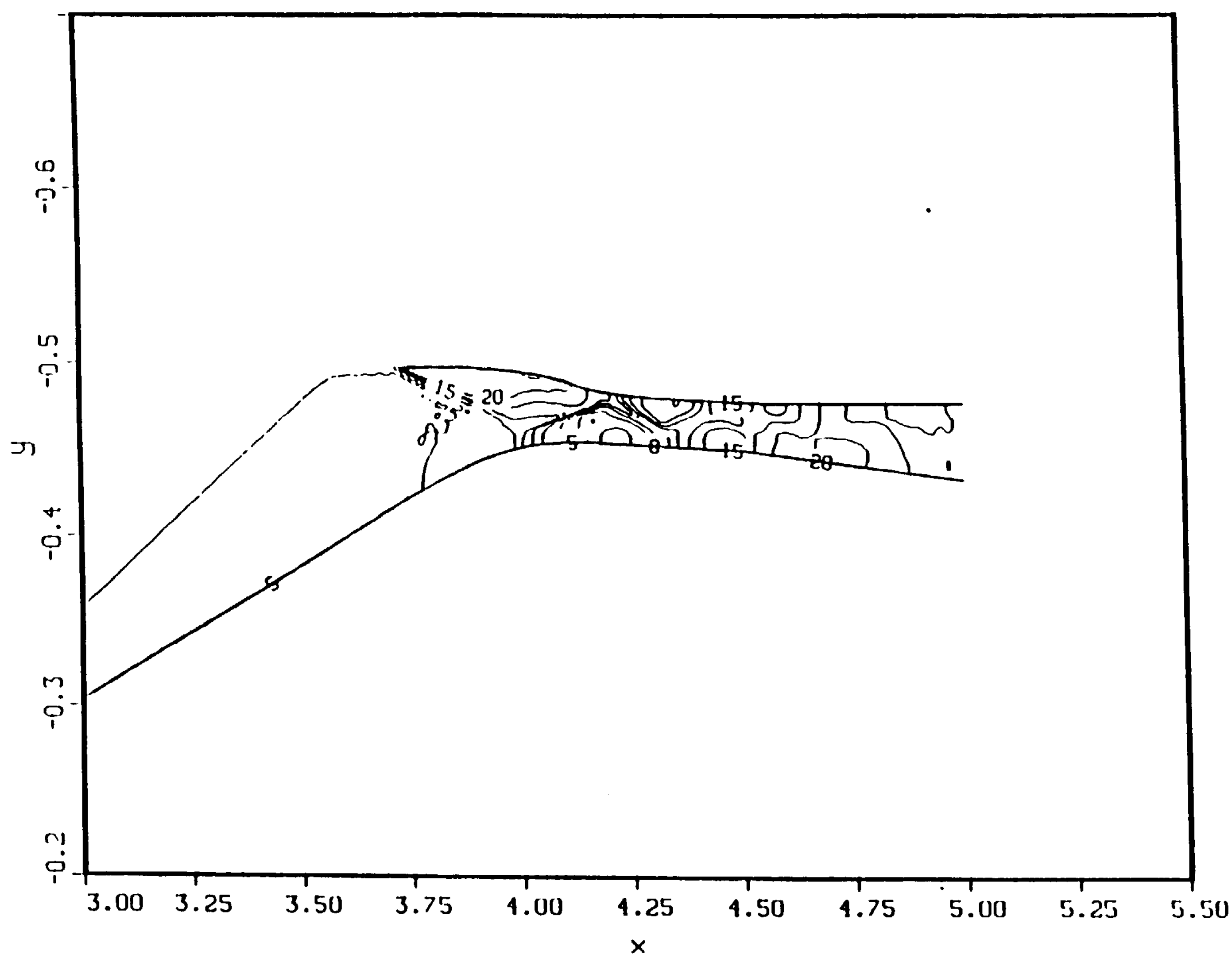

FIGURE 3 Concluded.
d) Internal Flow Detail, Pressure contours

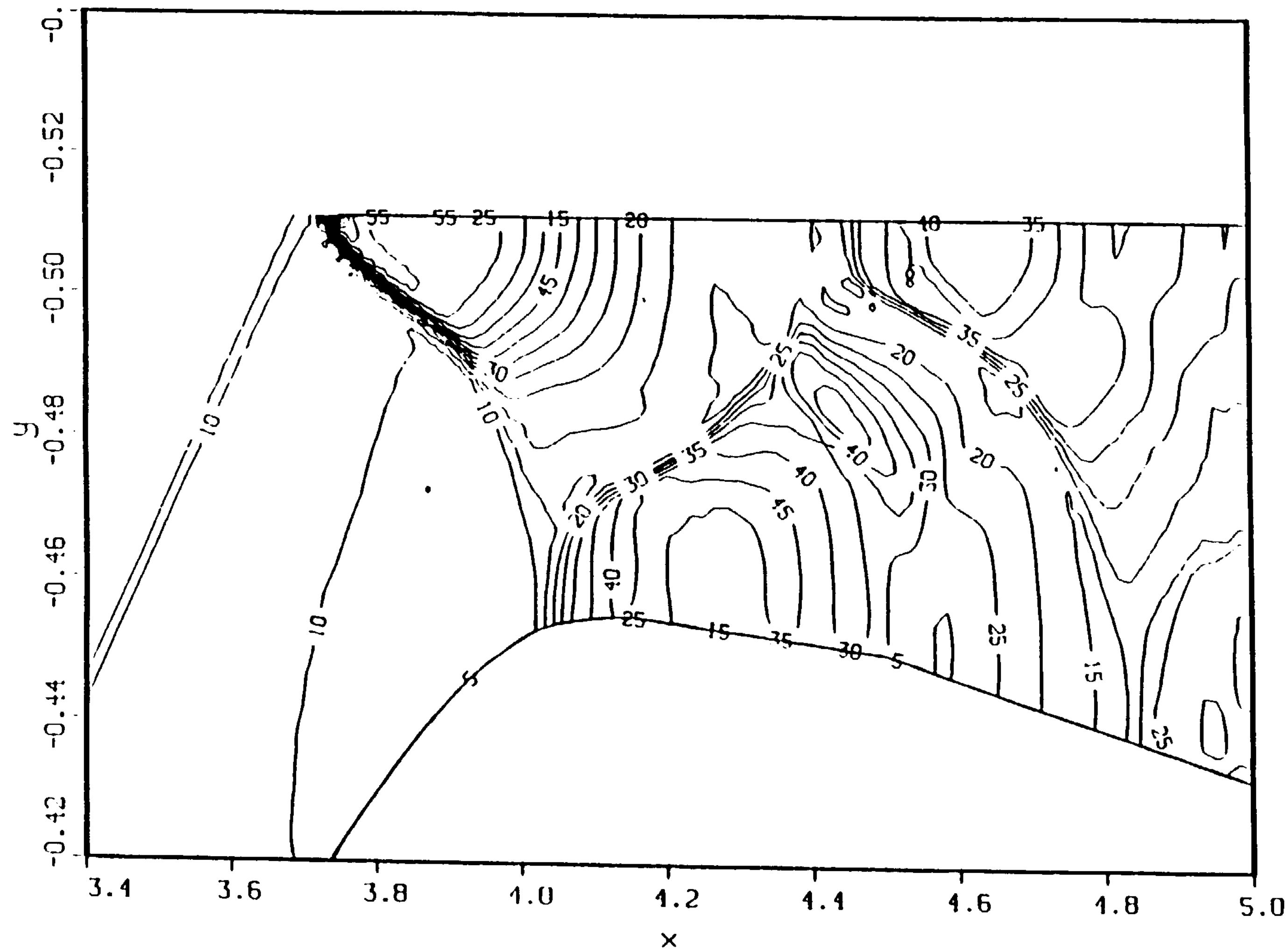

FIGURE 4 Static Pressure Ratio Contours, M = 15
a) Straight Cowl

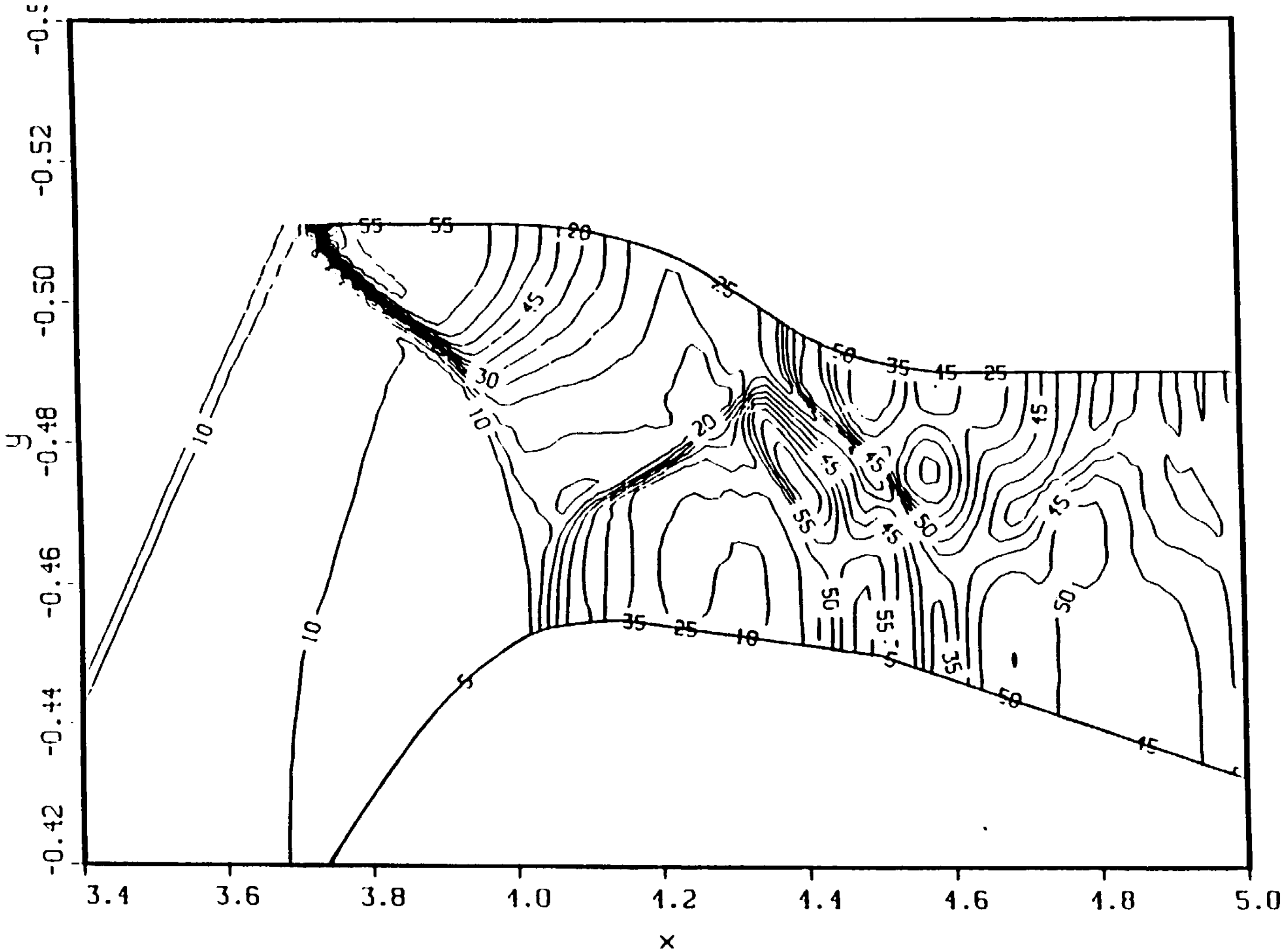

FIGURE 4 Concluded.
b) Contoured Cowl

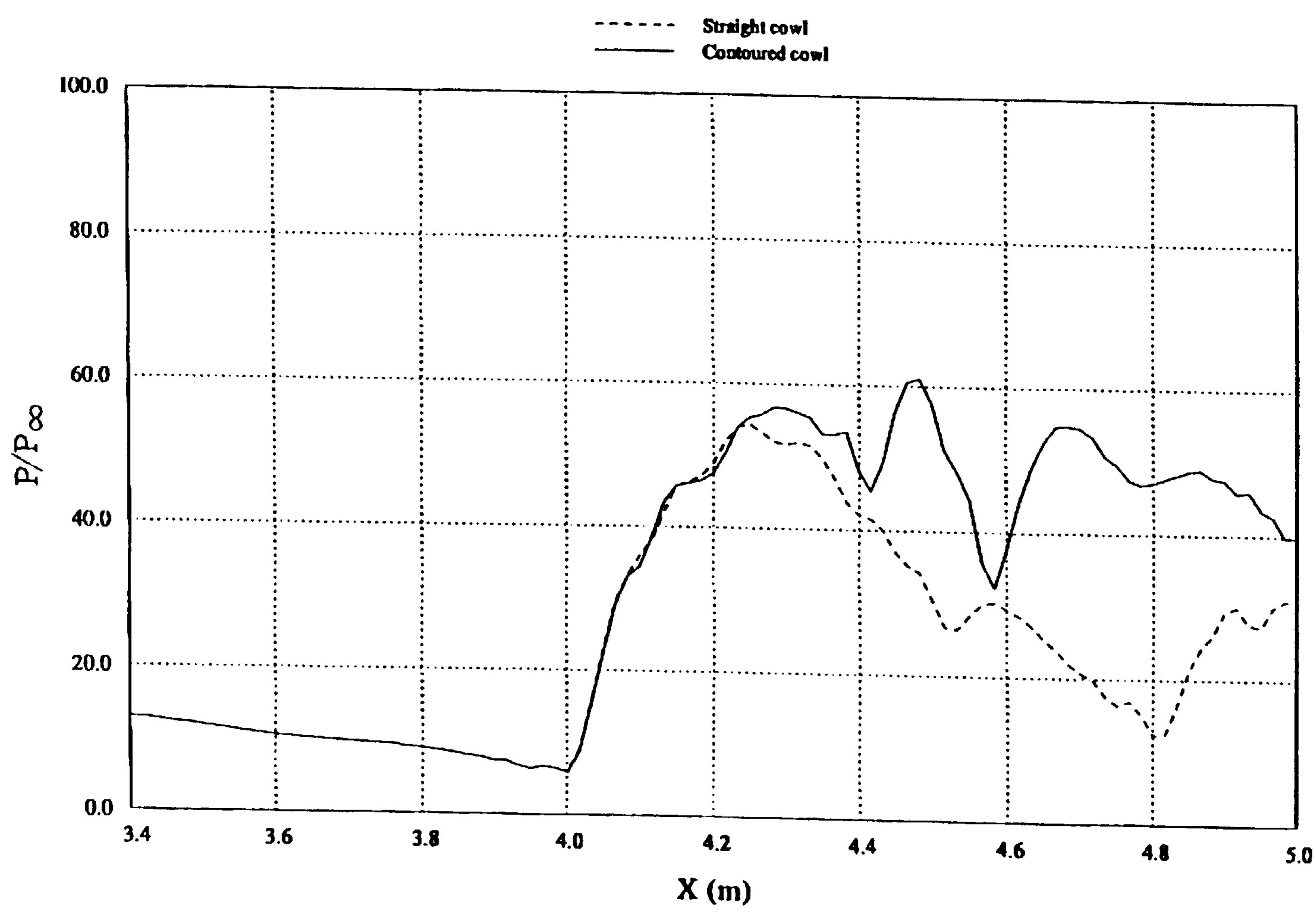

FIGURE 5 Comparison of Straight and Contoured Cowls, M = 15, Static Pressure Ratios on Ramp Surface.

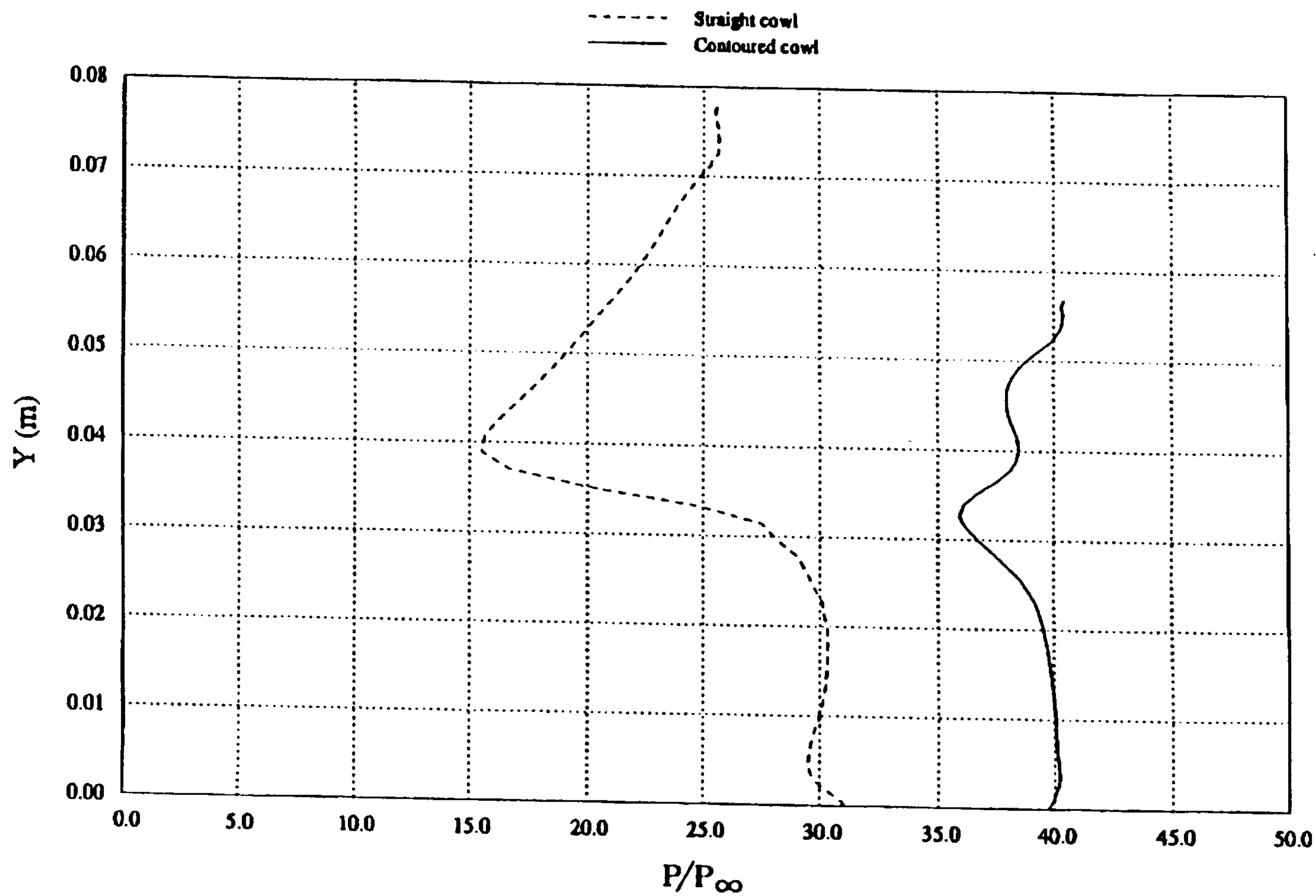

FIGURE 6 Comparison of Straight and Contoured Cowls, $M = 15$, Static Pressure Profiles at Exit Plane.